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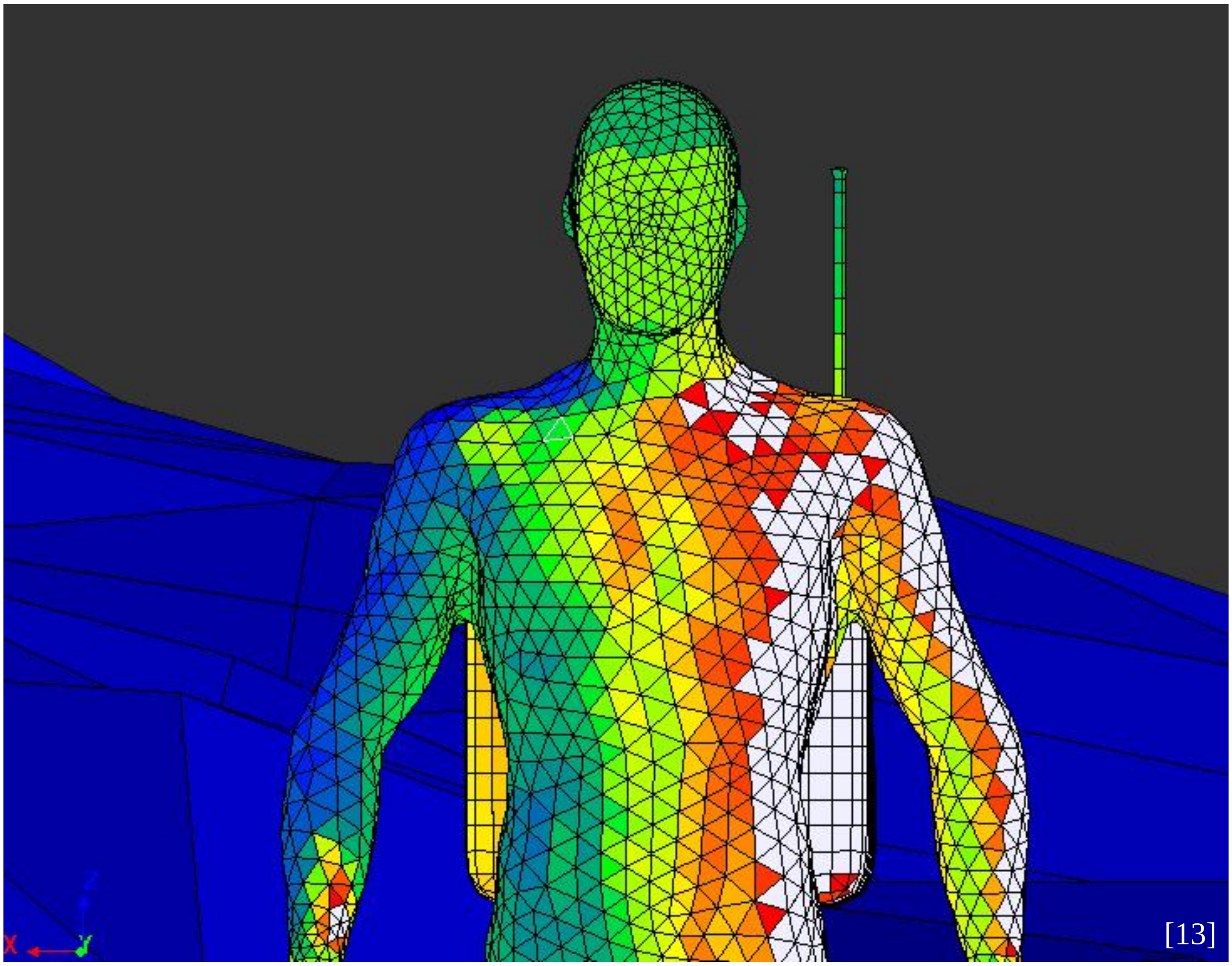
Chivalry or Survival
A Comparative Study on the Insulating Effects of Adipose Tissue, Winter Wear, and Physical Activity in Cold Climates



BEE 4530 – Computer Aided Engineering: Applications to Biomedical Processes

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SECTION I: EXECUTIVE SUMMARY

Adipose tissue levels, metabolic heat generation, and winter wear, all contribute to the body's ability to resist hypothermia during exposure to extremely cold environments. COMSOL software was used to model transient heat transfer in the human torso in a cold climate, providing the flexibility to change input parameters and investigate their cumulative role in maintaining body temperature.

Each model consisted of a skin, subcutaneous fat, muscle tissue, and inner core layer, with two models developed to simulate people with two different body mass indexes (BMIs). Both the 21BMI model and the 28 BMI model were evaluated wearing either a t-shirt, or a t-shirt and a wool coat. The models were exposed to -15°C air with a convective boundary condition, for one hour, and the temperature profiles were analyzed. The importance of appropriate winter wear was highlighted by a more than ten degree difference between the models, the ones with a wool coat, and the ones with only a t-shirt. As expected the increased thickness of the adipose tissue layer preserved the internal temperature of the core, showcasing the insulating capability of adipose tissue and its' role in preventing hypothermia. While the thicker adipose tissue layer led to higher internal core temperatures, it also impeded the conduction of heat to the outer layers resulting in lower skin temperatures. Exercise had a higher convective heat transfer coefficient, and as a result, the skin surface temperature was cooler. However, the increased metabolic heat generation in the muscle due to exercise, led to a higher core body temperature than that of the stationary model. Our findings indicate that after one hour of exposure to -15°C air it is unlikely a person will develop hypothermia. However, frostbite poses a real threat, especially for the 28BMI exercising model wearing a t-shirt, highlighting the importance of the appropriate winter wear.

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SECTION II: INTRODUCTION AND BACKGROUND

2.1 Introduction and Background

In this study, we sought to compare how different levels of adipose tissue, metabolic heat generation, and winter wear, help protect the body from hypothermia and frostbite using COMSOL computer modeling. Hypothermia is a broad medical condition indicating a core body temperature below 35C, with additional sub-classifications of mild, moderate and severe hypothermia. As the natural human body temperature is approximately 37C, even a modest two to three degree change in body temperature is sufficient to invoke physical symptoms such as extreme shivering, irregular breathing and tachycardia [11]. While a common cause of hypothermia is sudden immersion in cold water [8], extended exposure to cold and wind while wearing inadequate clothing can also lead to this debilitating condition. This investigation will use computational software to examine how parameters such as adipose tissue content, winter wear and physical activity effect body temperature during extended exposure to winter weather.

Advances in both computational power and biological knowledge have made the accurate modeling of biological systems possible. Modeling enables preliminary results to be generated, minimizing the need for expensive and time-consuming physical experiments. Furthermore, modeling is especially appropriate in scenarios that are either extremely difficult to obtain quantitative data or those which have ethical limitations, such as inducing hypothermia in test patients. Because of the previous factors, there have been several computer-modeling based investigations of heat transfer in humans. Previous studies have explored human heat loss [1],[6],[8], but none have been found that model how changes in adipose tissue, activity level, and clothing, interact to effect body temperature in cold climates.

In our investigation, a comparative study was conducted on two test cases. The first person had a Body Mass Index (BMI) of 28, the other had a BMI of 21, and this discrepancy allows us to investigate how different thicknesses of adipose tissue insulate the core in a cold environment. Both cases were evaluated over one hour periods while stationary or exercising, in order to understand how changes in metabolic heat generation affect susceptibility to hypothermia. All models were examined wearing either a t-shirt or a t-shirt and a wool coat. This allows for a direct qualitative comparison of the insulating value provided by a wool coat in comparison to that provided by a thicker adipose tissue layer. By incorporating these three key elements into a comparative study, we hope to achieve a greater overall understanding of how the body maintains its internal temperature over a range of conditions. Furthermore, we would like to apply this understanding to determine which protective factors have the greatest impact on preventing hypothermia to answer the question of chivalry or survival: specifically, who should run for help when stranded after the car breaks down, a 21BMI woman with an XS coat or the 28BMI man wearing only a t-shirt.

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2.2 Design Objectives

The design objectives incorporated into our model are listed below:

- Analyze two models with different thicknesses of adipose tissue. The 21BMI model had 17mm of adipose tissue while the 28BMI model had 41mm.
- Examine both models under both stationary and exercising conditions, with the additional metabolic heat generation from exercise accounted for by increasing the heat generation in the muscle subdomain by a factor of ten [11]. Furthermore, when exercising, the convective heat transfer coefficient increases to 50W/m^{2}K from 20W/m^{2}K when stationary.
- Model heat transfer through a rectangular, axisymmetric cross section of the body, using one dimensional conduction with subdomain specific source terms. The different sections were body core, muscle, adipose tissue, and skin. On top of the skin layer, both models had a thin air layer and a thin layer of clothing (T-shirt). On top of the thin clothing layer, alternate versions of the 21BMI and 28BMI models had a wool coat.
- Determine the temperature variation of the core layer as a function of time for 1 hour.
- Determine the temperature profile in both models after one hour of both stationary and exercising activity levels.
- Determine to what extent adipose tissue content, physical activity, and clothing insulate the body.
- Validate our model using data from previous experimental studies on hypothermia.

2.3 Assumptions

The assumptions made for the model that we created are as follows:

1. The COMSOL simulation is modeled as 2D axial symmetry and transient heat conduction.
2. The model considers the Human Thorax (torso) only.
3. Metabolic heat generation is present in all tissue layers at varying levels.
4. Heat produced by blood flow is present in all tissue layers in different amounts due to different blood flow and perfusion rates.
5. The core body (organs, bones, visceral tissues) is modeled as a lumped parameter.
6. Change in outside air temperature is negligible.
7. Initially, the temperature of the body tissues and clothing is 37°C.

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2.4 Governing Equations

The main equations we used as the governing equations for our model are listed below. The first is a 1D heat transfer equation including a transient, conductive, and generation term. The second is the bioheat equation, which models heat generation due to blood flow.

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p}\frac{\partial^2 T}{\partial x^2} + \frac{Q}{\rho c_p}$$

$$Q = Q_{met} + \rho_b c_b v_b (T_a - T)$$

2.5 Problem Schematic:

In order to approach this problem we modeled transient heat transfer in the human torso due to cooling, while varying the degree of subcutaneous fat and the activity level of the human. In order to make the modeling feasible for the scope of the project, we chose to use an axi-symmetrical 1D approach, which was modeled in COMSOL using a 2D geometry in order to improve the visualization of results. Similar to models existing in the literature [8], our model of the torso consists of a skin layer, subcutaneous fat layer, muscle tissue layer, and the inner core (other visceral tissues, organs, and bones). This model will then be cooled by the outside air using a boundary condition determined by the wind temperature and speed. The anatomical dimensions used for the thickness of the muscle and fat layers were found in a study which utilized ultrasound to make measurements of muscle and fat thickness [9].

Additionally, the anatomical effects of increased BMI were obtained from a radiographic study of individuals with varying BMIs. Depending on the height of the individual, a 15lb increase in weight corresponds to approximately a +2 increase in Body Mass Index (BMI). According to the literature; this increase in BMI can be related to a 6.5mm addition of fat to the core radius [10]. Clothing was modeled in simplified manner that includes the thermal properties of the clothing itself, but also includes a fixed, insulating, “dead air” pocket between the skin and clothing. Schematics of the two models are shown below. Figure 1 shows the 28 BMI model and Figure 2 displays the 21 BMI model.

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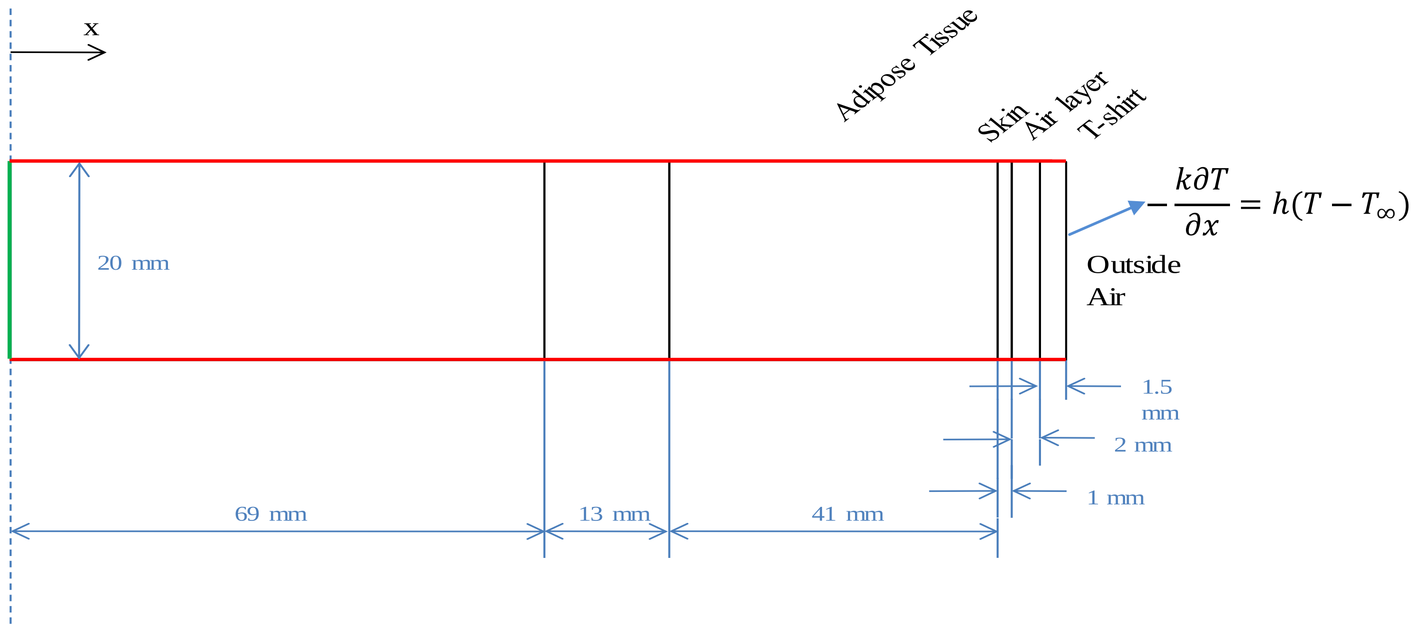

Figure 1: Schematic of the Human Thorax (torso) with a 28 BMI and only wearing a T-shirt. The red boundaries indicate insulation (heat flux is zero) thus all heat transfer is in the x-direction. The model is axisymmetric about the dashed line. The green line represents the core body temperature where heat flux is zero due to axisymmetry. The ambient air temperatureT_∞, is 15°C.

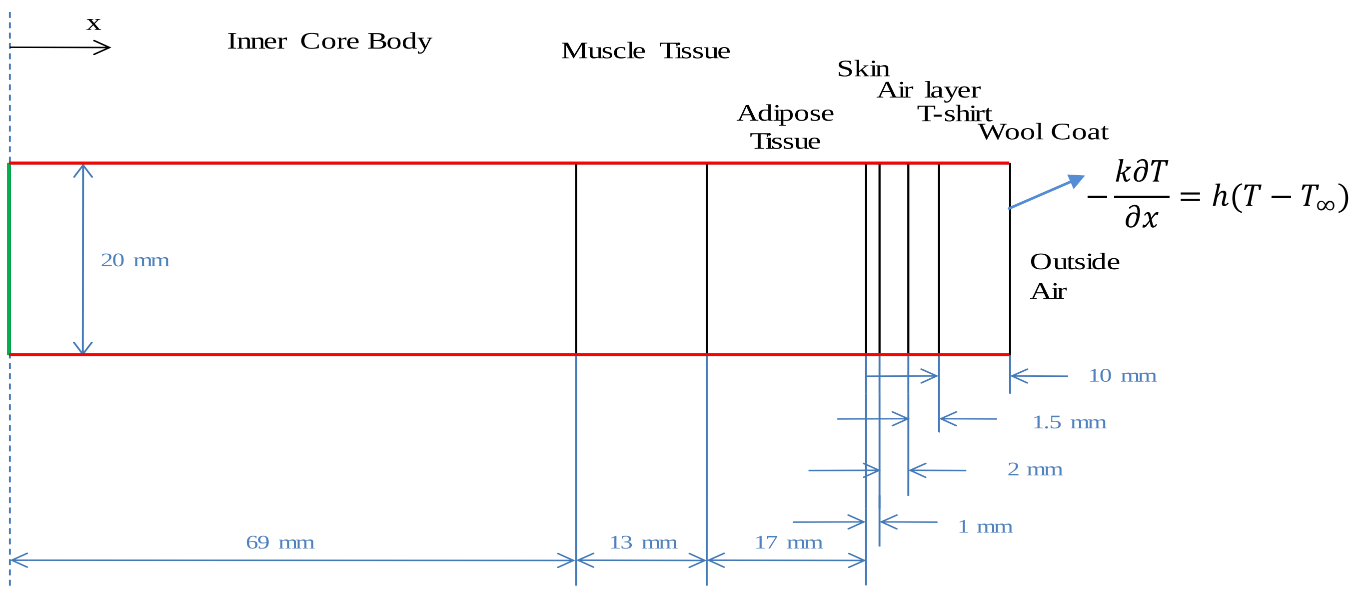

Figure 2: Schematic of the Human Thorax (torso) with a 21 BMI and a thick wool coat. The red boundaries indicate insulation (heat flux is zero) thus all heat transfer is in the x-direction. The model is axisymmetric about the dashed line. The green line represents the core body temperature where heat flux is zero due to axisymmetry. The ambient air temperatureT_∞, is 15°C.

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2.6 Model Design and Conditions

In human heat transfer models, it is common for the inner core of the human body to be modeled as a single region, despite the fact that it is composed of many different tissue types [1] [8]. This inner layer contains organs, bones, and other visceral tissues below the muscle. Additionally, due to the thermal mechanisms in place to regulate body temperature the internal core is maintained approximately uniform in temperature. Due to the overwhelming complexity of these phenomena, we chose to model the core as a lumped parameter, meaning that its thermal conductivity is essentially infinite. Therefore the temperature of the core will fluctuate uniformly as heat is lost from the model.

In addition to considering the heat transfer due to convective heat loss on the skin surface, heat generation in the tissues and heat transfer due to blood flow were considered. The bioheat equation commonly used in biological heat transfer models was implemented using physiological data from the literature (Table 1A Appendix A) and a time dependent systemic blood temperature supplied to each tissue. The basal metabolic heat generation values of each tissue type were determined through a literature search and are included in Appendix A. To quantify how exercise changes the metabolic heat generation and thus the body's ability to maintain a constant core temperature, both stationary and exercise situations were tested. It is well-known that exercising produces heat. However, it does not solely promote heating because running or walking in a cold environment increases the rate of heat loss at the skin surface due to convection. To model the increased heat generation due to exercise, our model increased the metabolic heat generation in the muscle layer by a factor of ten, which has been previously observed [11].

SECTION III: RESULTS AND DISCUSSION

3.1 Modeling the Temperature Profile during Prolonged Exposure

The temperature profile of a human cross section was modeled in COMSOL using the above schematics and listed parameters. A constrained edge element distribution of rectangular elements was used in mesh convergence analysis outlined in Appendix C. The simulation was run in -15°C air for different exposure times and the cross sectional temperature profile plot was generated. Figure 3, represents the loss of heat with extended exposure times of a 21 BMI person with a wool coat when stationary. As seen in Figure 3, the largest temperature gradient occurs in the adipose tissue, confirming adipose tissue as a biological insulating agent. This insulation effect can be seen by the 7°C temperature change from approximately 27°C at the skin surface to 34°C at the fat-muscle interface. Additionally, the temperature in the core steadily decreases with time. However, after 5 hours the core is still above the onset temperature of hypothermia, which occurs around 35°C. This behavior during long exposure times is a

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limitation of our model, as it would be expected that hypothermia would develop after such a prolonged exposure. The model was designed for the consideration of shorter exposures, so it does not take into account long term physiological events, such as the depletion of glucose stores, which lead to decreased heat production. A more advanced model would include parameters designed to more accurately capture the physiological effects of prolonged exposure to the cold. Despite the model's limitations in long exposures, both our exercise and stationary models were validated with experimental data for a two hour exposure

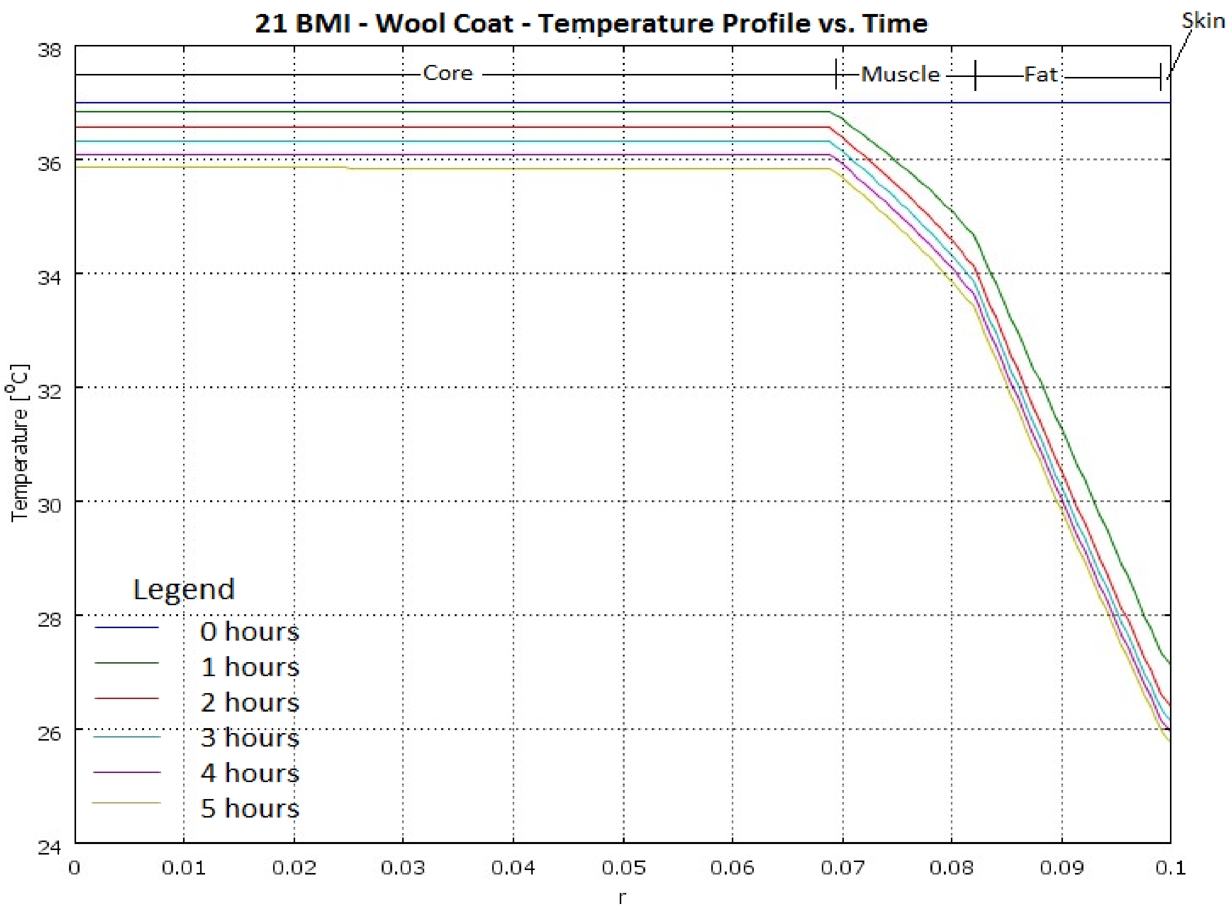

Figure 3: Plot of the temperature profile of the Human Thorax (torso) with a 21 BMI model and a thick wool coat while stationary at various exposure times to -15°C weather.

3.2 Modeling the Skin Surface Temperature with Time

During exercise, the convective heat transfer coefficient increases because the body is exposed to the cold windy air while the metabolic heat generation in the muscle increases ten-fold. As a result, exercise decreases the skin surface temperature but the increased generation term maintains the core temperature, combating hypothermia. As depicted in Figure 4, after a one hour exposure to the cold, none of the models were in danger of developing frostbite, which occurs when the skin drops below 5°C. However, if one considers that this reflects the core skin

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surface temperature, than the 28BMI exercising model wearing a t-shirt has likely developed frostbite in his extremities such as his hands.

Initially, all of the skin surface temperatures are 37.2°C but when placed in a cold environment, the skin surface temperature decreases in an exponential fashion. As expected, the wool coat resulted in the highest skin temperatures because it more effectively insulated the skin from the windy, cold environment. Furthermore, despite the increased heat generation in the muscle layer, the higher convective heat transfer coefficient accompanying exercise, $50W/m^2K$ as compared to $20W/m^2K$, had a larger impact on the skin's temperature. Interestingly, the 28BMI model with the thicker adipose tissue layer consistently had lower skin surface temperatures at the end of the one hour period, as seen in Figure 4. This suggests that while the fat layer is effective at insulating the core from the cold external climate, it also drastically reduces the conduction of heat from the core to the skin. Therefore, people with higher body mass indexes and thus, thicker layers of adipose tissue, may feel warmer but they are more susceptible to frostbite. Referring to our original hypothetical scenario, it is then advised that the 21BMI woman with a coat runs for help as the 28BMI man in a t-shirt stays in the car reinforcing the notion that chivalry is dead.

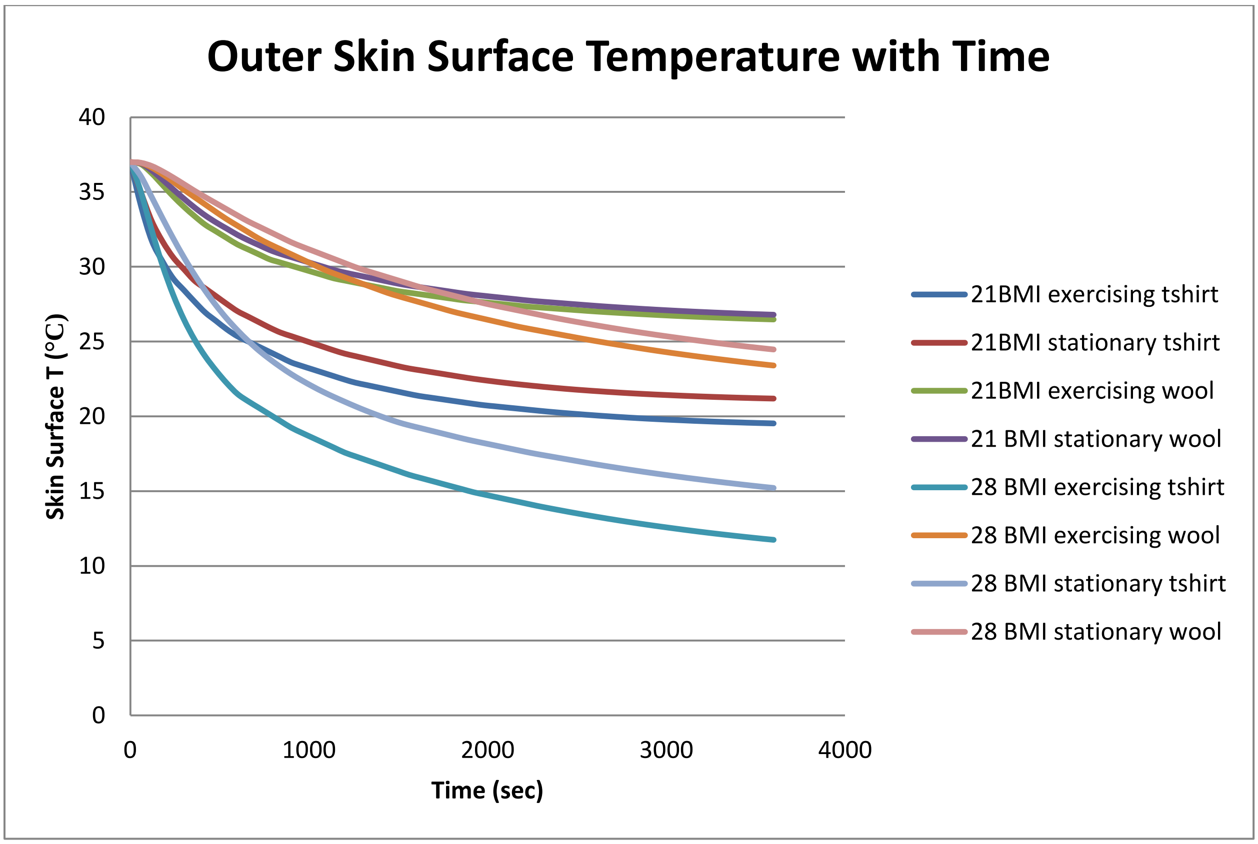

Figure 4: Outer skin surface temperature for both the 21 and 28BMI models under various conditions after 1 hour exposure to -15°C air. The outer skin surface was defined as the point in the skin layer that interfaced with the stagnant air in between the skin and the t-shirt.

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3.3 Modeling the Temperature Profile from the Edge of the Body Core to the Skin Surface

The results of temperature profile from the edge of the core to the skin after running the 21 BMI and 28 BMI models for each of the four scenarios are shown below in Figures 5 and 6. From Figure 5, the 21 BMI model demonstrated the highest core temperature while exercising with a coat, and the highest skin temperature while stationary with a coat. The lowest core temperature was found in the stationary model with only a t-shirt, and the lowest skin temperature was found in exercising model with a t-shirt. The results of the 28 BMI model in figure 6 showed the same pattern of results for the four scenarios as in the 21 BMI model, which was to be expected. However, the 28 BMI model appeared to experience larger drops in skin temperature compared to the 21 BMI model. This can be attributed to the greater thickness of the adipose tissue in the 28 BMI model than the 21 BMI model, which makes heating to from blood flow from the core to the skin less effiecient than in the 21 BMI model.

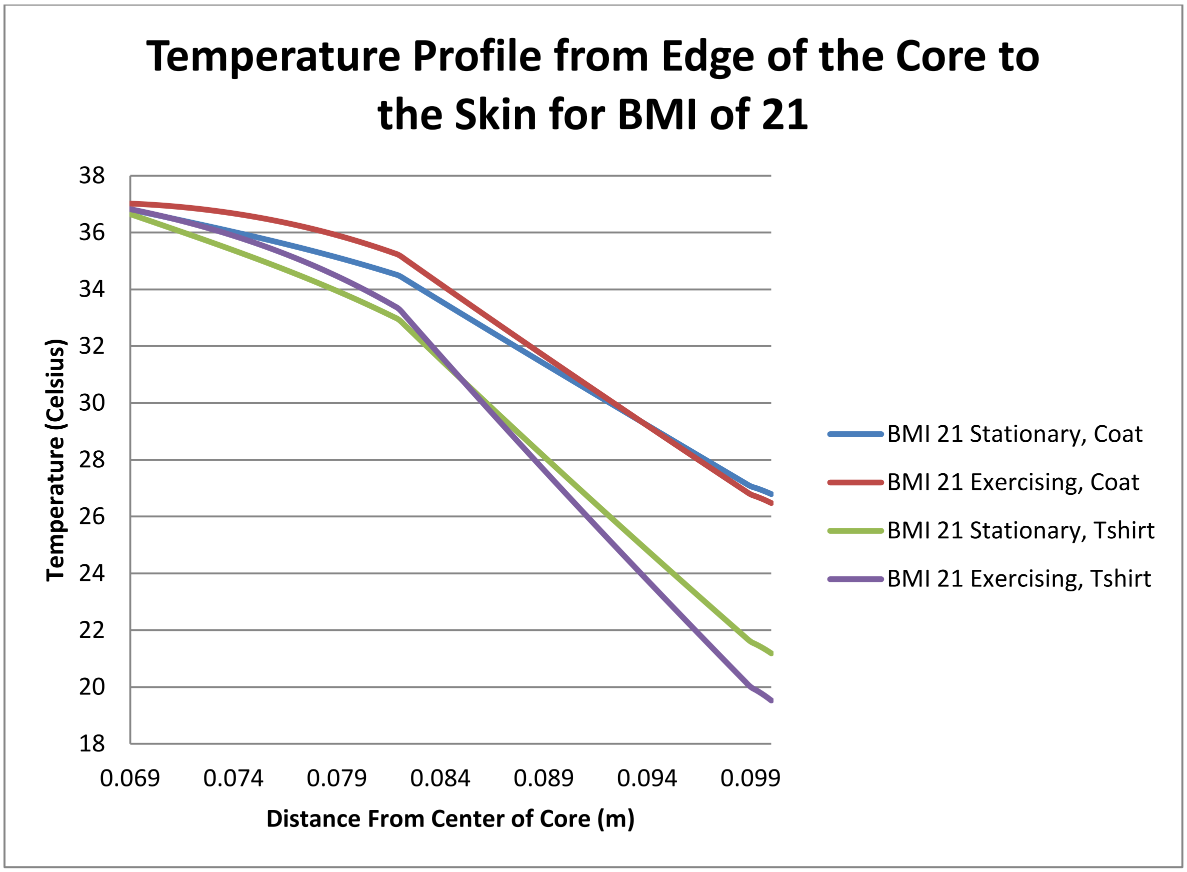

Figure 5: Plot of temperature from the edge of the core to the skin surface for the 21BMI model under various conditions after 1 hour exposure to -15°C air.

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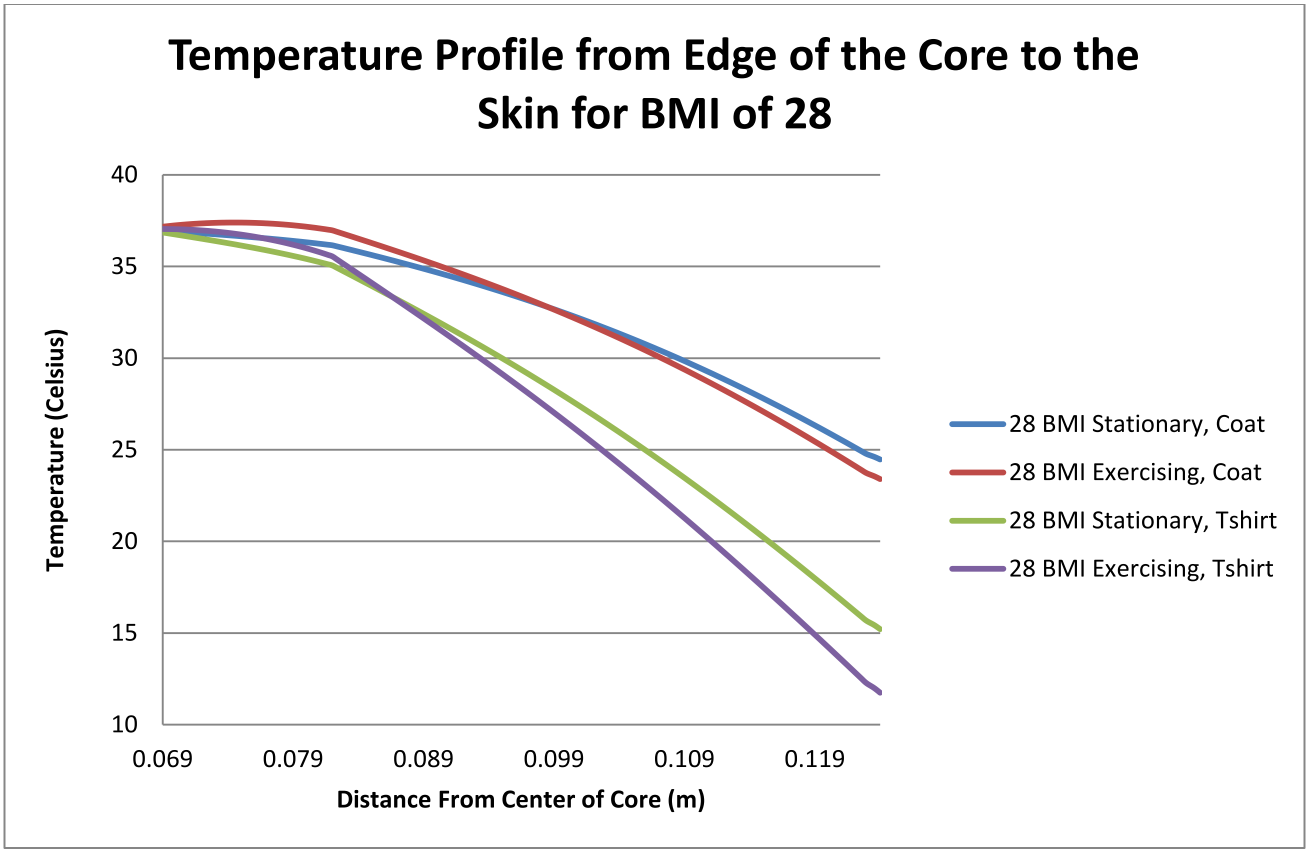

Figure 6: Plot of temperature from the edge of the core to the skin surface for the 28BMI model under various conditions after 1 hour exposure to -15°C air.

3.4 Modeling the Temperature at a Point within the Body Core over Time

The change in temperature at a point within the body core over time for eight different cases is shown below in figure 7. All eight scenarios were simulated for one hour exposure to an outside temperature of -15 degrees Celsius. While exercising, the 28 BMI model with a coat displayed the highest core body temperature. The core body temperature actually rose instead of cooling down. These results illustrate the combined effectiveness of adipose tissue, exercise, and winter wear in protecting the core body temperature. The 28 BMI model while exercising, with either a coat or t-shirt, was warmer than all of the 21 BMI models. This highlights the insulating abilities of adipose tissue, as the exercising 28 BMI model with only a t-shirt was warmer than the exercising 21 BMI model with a coat. The data displayed the same pattern for the stationary results. With and without a coat, the 28 BMI model under stationary conditions was warmer than both the stationary 21 BMI models. The stationary 21 BMI model with only a t-shirt showed the biggest drop in core temperature. This scenario was predicted to have the largest drop in core body temperature due to having the least amount of adipsoe tissue, no additional metabolic heat generation from exercise, and only a t-shirt. Another interesting outcome is that the 21 BMI model while exercising with a t-shirt, was cooler than both 28 BMI stationary models and even the 21 BMI stationary model with a coat. This result demonstrates how additional heat

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generation from exercise cannot protect the body as effectively as adipose tissue or winter wear for long periods of time.

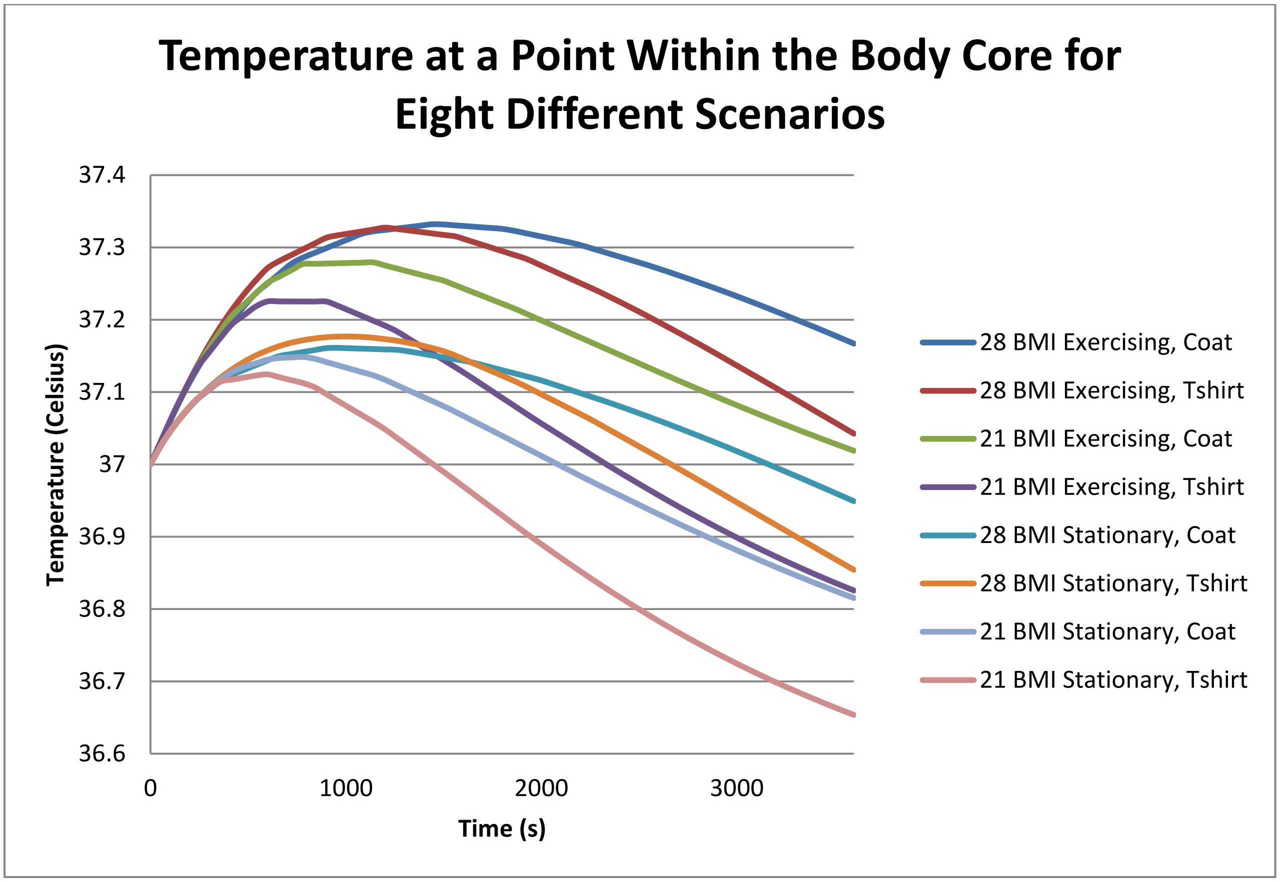

Figure 7: Temperature at a point within the body core for both the 21 and 28BMI models under various conditions after 1 hour exposure to -15°C air.

3.5 Accuracy Check

In order to validate our model, we searched in the literature for similar situations to those tested in our model. In the paper by Xu and Warner [1], several sets of experimental data are presented. Each experimental set had a large amount of inter-subject variability because each person's basal metabolic temperature naturally started at a different point. So for our comparisons, the data is plotted from the highest and lowest temperature experimental subjects in order to demonstrate the range of experimental data. The first situation, shown in Figure 8, measured experimentally was a nude subject exercising at 12°C. We removed the clothing layers from our model and adjusted the air temperature and initial temperature to match the experimental conditions. As the experiment did not specify the BMI of subjects, we modeled both the 21 and 28 BMI models under these conditions. In the experimental curves, it can be seen that initially the subject's core warms, but with time it cools towards the air temperature. This same trend is observed in both of our model's data. Our 28 BMI model appears to more closely align with experimental data than the 21 BMI model so it is possible that the experimental subjects were of a higher BMI than 21.

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Overall there is relatively good agreement between the experimental data for nude exercise at 12°C and our computational model under the same conditions.

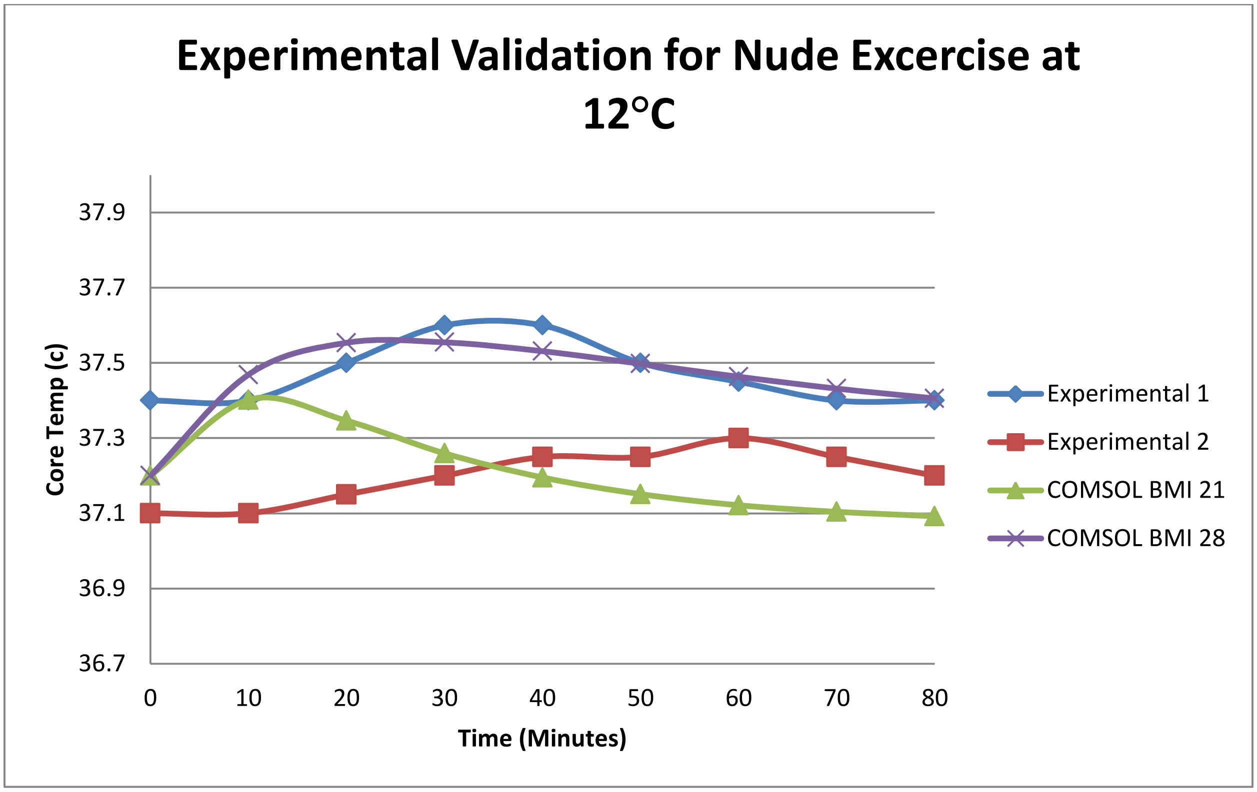

Figure 8: Comparison of experimental and COMSOL model for a nude subject exercising at 12°C. Lines marked with the diamonds and squares are respectively the highest and lowest temperature subjects from the experimental data [1].

The second experimental situation compared to our COMSOL model is that of a nude, stationary subject at 1°C, and the results are shown in Figure 9. Similarly to the previous model, there was a huge amount of variability in the experimental data [1] so the warmest and coldest individuals were selected to represent the range of experimental data. Our model was adjusted to most closely match the experimental conditions. The BMI 28 model seems to most accurately agree with the general trend of the experimental group by demonstrating a slow warming and then gradual cooling. The BMI 21 model appears to lose temperature more quickly than the experimental data which is reason to speculate that the experimental models may have been of a higher BMI. Again, there is relatively good agreement between the model and the range of experimental data provided.

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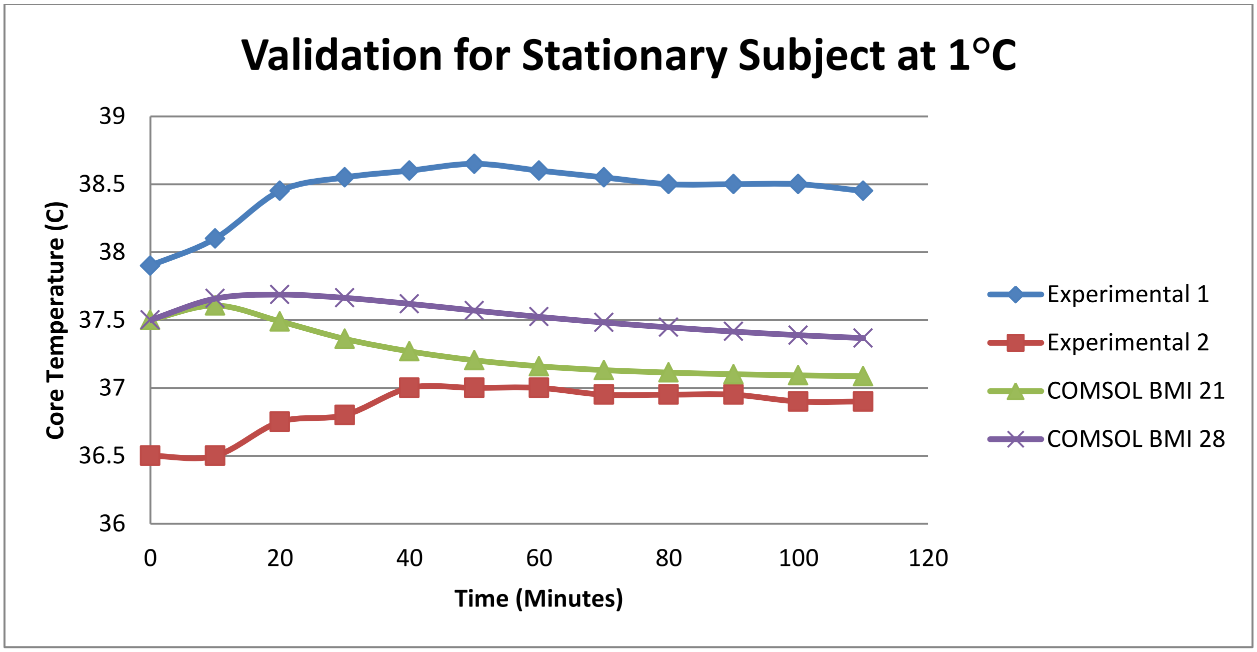

Figure 9: Comparison of experimental and COMSOL model for a nude subject stationary at 1°C. Lines marked with the diamonds and squares are respectively the highest and lowest temperature subjects from the experimental data [1].

3.6 Sensitivity Analysis

A sensitivity analysis was performed for parameters Q_{met}, heat transfer coefficient at the surface of the model (h), thermal conductivity of the clothing (k), and blood flow rate (V_b) for each of the two models. The value of each parameter was increased and decreased by 10% and the temperature of the point (0.0345,0.01) was plotted. In Figures 10 and 11, we can see that the thermal conductivity of the clothing (k) has a greater importance in influencing core temperature in a model with a lower amount of adipose tissue. This confirms that the extra adipose tissue is an important factor insulating the core in the 28 BMI model, and that the clothing is important in insulating the core in the 21 BMI model. As we can see in both graphs a 10% change in parameter value does not induce a significant change in the core temperature of our model. From this we can conclude that our model is not extremely sensitive to the input parameters listed. Therefore, small errors in parameter values will not significantly affect the core temperature in our model.

A sensitivity analysis was also performed on average skin temperature, as seen in Figure 12, using the same four parameters, $Q_{met,}$ k, h, and V_b for a model wearing only a t-shirt. From this analysis we found that the heat transfer coefficient and the blood flow rate had a significant effect on the skin surface temperature. Blood flow rate also has a significant impact on the temperature of the skin.

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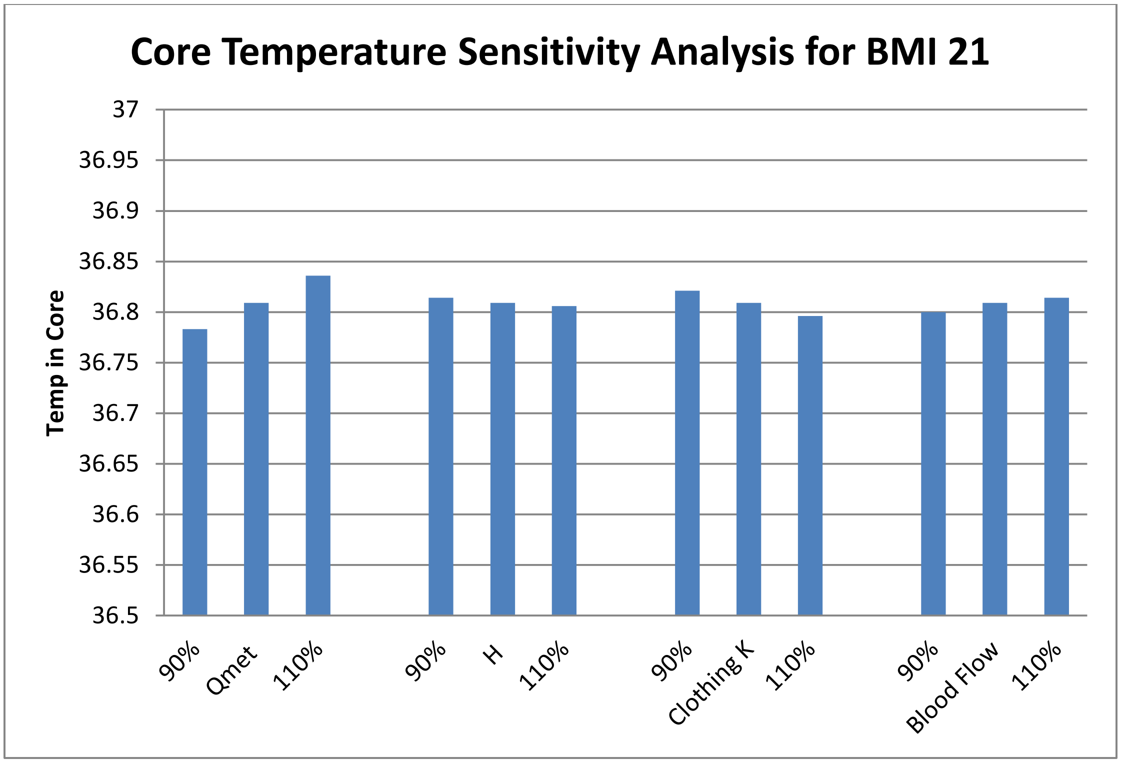

Figure 10: Sensitivity analysis of the parameters, Q_{met}, h, k of the clothing, and blood flow (V_b) and how they affect the heat transfer within the model for a stationary person with a BMI of 21 wearing a coat.

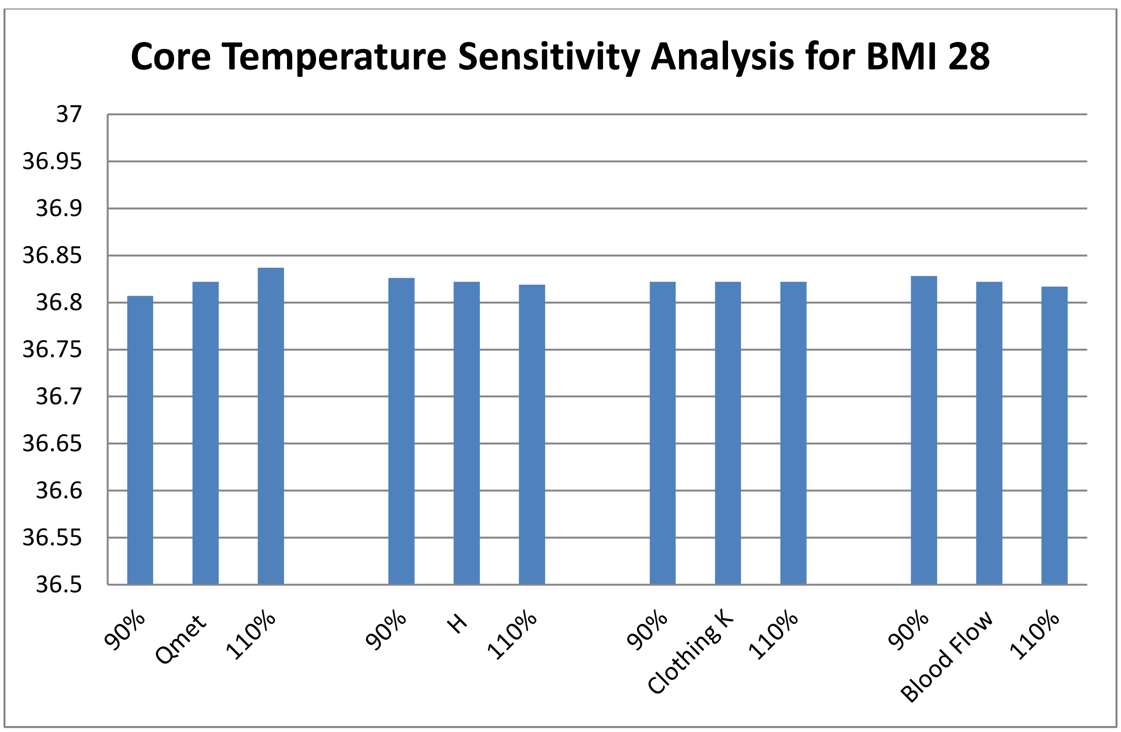

Figure 11: Sensitivity analysis of the parameters, Q_{met}, h, k of the clothing, and blood flow (V_b) and how they affect the heat transfer within the model for a stationary person with a BMI of 28 wearing only a t-shirt.

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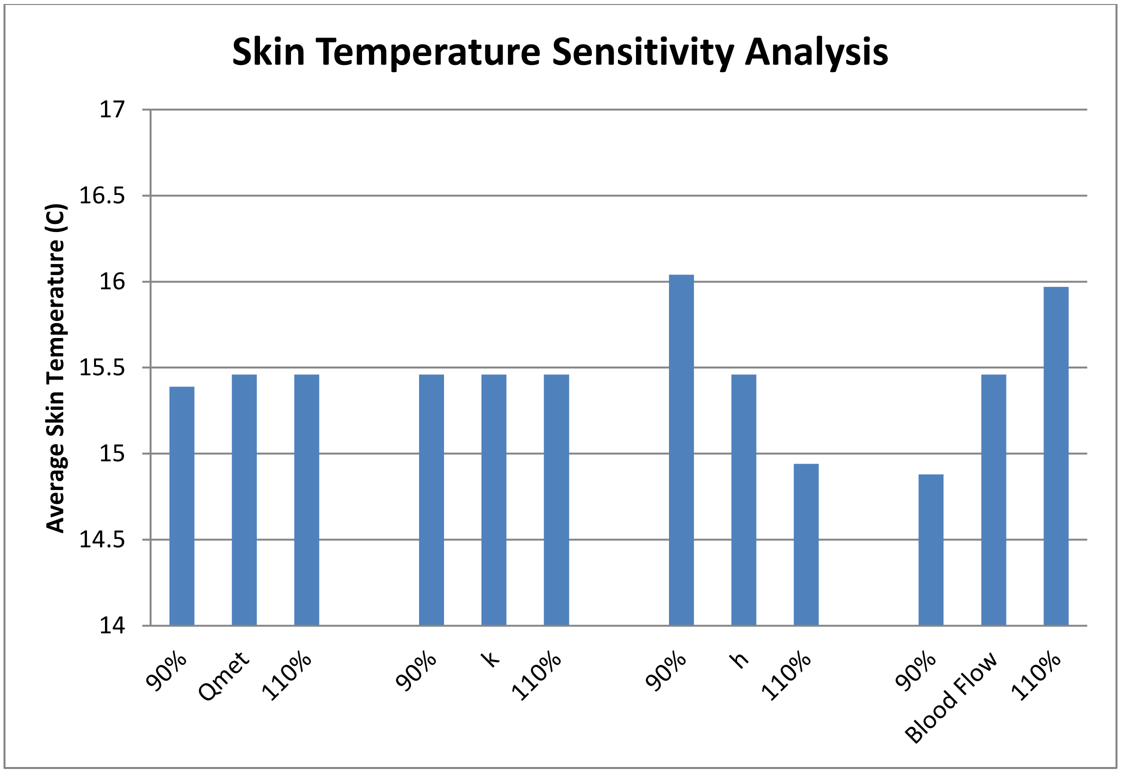

Figure 12: Sensitivity analysis of the parameters, Q_{met}, h, k of the clothing, and blood flow (V_b) and how they affect the average temperature within the skin for a stationary person with a BMI of 21 wearing only a t-shirt.

SECTION IV: CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions and Design Recommendations:

We created a model of the human torso to predict the drop in core temperature during periods of exposure to subzero temperatures. We sought to examine the insulating effects of adipose tissue and varying amounts of winter wear as well as the effect exercise on core temperature. From our results we can see that for one hour exposure to -15°C air core temperature is well insulated and there is not a large drop in temperature due to adequate insulation from adipose tissue and winter wear. From Figures 5 and 6, we can see that skin surface temperature drops significantly for the models with only a t-shirt on. From this we can conclude that the wool coat is crucial in maintaining skin surface temperature. We also see that the skin temperature in the 28 BMI model drops much lower than the 21 BMI model. This is most likely from the increased adipose tissue thickness. A thicker layer insulates the core preventing heat from being conducted out of the body to warm the skin. From this we see that although a higher level of adipose tissue will help prevent the onset of hypothermia, the risk of frostbite increases if the proper protective winter wear is not worn. We recommend that no matter the amount of adipose tissue proper winter wear must be worn to prevent frostbite.

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From our sensitivity analysis, Figures 10, 11, and 12, we learned that the thermal conductivity of the clothing (k) is more important in influencing core temperature in a model with a lower amount of adipose tissue. This reflects the high buffering capacity a thicker adipose tissue layer provides. The sensitivity analysis performed on the skin showed us that the heat transfer coefficient and blood flow rate have a significant effect on skin temperature. The heat transfer coefficient should have a significant effect on skin temperature. This is what we expect to see because you lose heat faster when the wind is blowing faster (a higher heat transfer coefficient.) Blood flow rate effecting skin temperature makes physical sense since the skin is not generating much heat on its own and must rely on heat being supplied by the blood in order to maintain warmth. Overall we found that factors that should impact the skin temperature do have an effect and factors that should have little impact on skin temperature like Q_{met} do not have a significant effect.

This model, with many input parameters, can be used to determine the time for the core to reach hypothermia for a variety of different environmental scenarios. Furthermore, this model can be utilized to determine the amount of clothing necessary to maintain core temperatures for different time periods in subzero temperatures. Or, it could be used to evaluate the insulating effect provided by a new line of clothing without subjecting a person to product testing in cold climates. Finally, the model can be used to determine when frostbite occurs during exposure to subzero temperatures. This basic understanding of how the body temperature is influenced by different insulating and protective factors can be applied to making recommendations for wilderness survival, clothing design for obese populations or how best to stay warm when making the trek to class each day.

4.2 Model Limitations

When attempting to implement any complex real-life problem in computer modeling software certain realistic limitations need to be taken into account. Due to the simplifications that were used in order to make a workable model in COMSOL, some of the complexities in the geometry have been lost. These simplifications were necessary because a model of the human torso is a very complex 3D geometry that would take increasing amounts of computing time. The body is a very complicated organism and many of the feedback systems and other regulatory mechanisms that control metabolism levels and maintain core temperature are not well known and cannot be used in our model.

4.3 Future Work

To make our model more realistic in order to approximate temperature within the core and through the trunk there are several factors improvements that can be made to our model. At the present moment our model deals with the core as a lumped parameter. We assumed that all the organs and bones of the core are all uniform in structure and physical properties. In order to

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more accurately model heat transfer effecting core temperature we would need to incorporate the bones and organs into our model. This change would eliminate the need for lumped parameter analysis in COMSOL which has been implemented by an extremely high thermal conductivity. In our current model we have arterial blood temperature and volumetric flow rate of blood varying linearly as the body cools and time progresses. An equation that accurately predicts arterial blood temperature and the volumetric flow rate of blood through different tissue types as the body cools would drastically increase the accuracy of our model. These changes will allow our model to more accurately predict temperature profiles for extended periods of time in COMSOL.

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SECTION V: APPENDICES

5.1 Appendix A - Input Parameters

	k (W/mK)	ρ (kg/m^3)	Cp (J/kgK)	Qmetabolic (W/m^3)	Velocity of Blood: V (m^3/s)
Core	510*[1]	1700[1]	1960.9[1]	1798[1]	0.00184[1]
Muscle	0.41[1]	1040[1]	2445.9[1]	684[1]	5.50E-04[1]
Fat	0.21[1]	920[1]	1243.1[1]	368[1]	0[1]
Skin	0.42[1]	1100[1]	2348.5[1]	349[1]	0.001278[1]
Air	0.0257[5]	1.293[5]	1005[5]	0	N/A
Cotton T-shirt ‡	0.03[2]	370 [7]	1338.9[3]	0	N/A
Wool Felt Coat	0.07[2]	150[4]	1380[3]	0	N/A

Table 1A - The time period that was studied was 3600 seconds, which is equivalent to 1 hour In the bioheat equation, the density, and specific heat of blood, were estimated as 1060kg/m^3 and 3600 J/kgK, respectively.
‡ White Cotton, Twill Weave

*Lumped parameter analysis approximated by drastically increasing the conductivity across the core layer. Heat transfer coefficient at outer edge was estimated as 20W/m^{2}K for stationary and 50W/m^{2}K for walking through the windy frigid weather.

5.2 Appendix B - COMSOL Specifications

We used COMSOL Multiphysics software, implementing the UMFPACK direct solver. The time step used was 60 seconds and was run for a total of 3600 seconds (one hour). The relative tolerance used was 0.01 and absolute tolerance was 0.0010.

5.3 Appendix C - Mesh Convergence

For the mesh convergence analysis we chose to use the mean temperature within the adipose layer. In Figure 1A, it can be seen that there is very little variation as the mesh elements increase. For an acceptable tolerance of 0.05 the mesh converges after approximately 1950 mesh elements. The value of average adipose tissue temperature does not change outside the acceptable tolerance level after 1900 mesh elements. From this we can conclude that 1950 mesh elements is sufficient to give a solution that is mesh independent for our heat transfer model. Figures 2A and 3A are graphic representations of the final mesh for both models.

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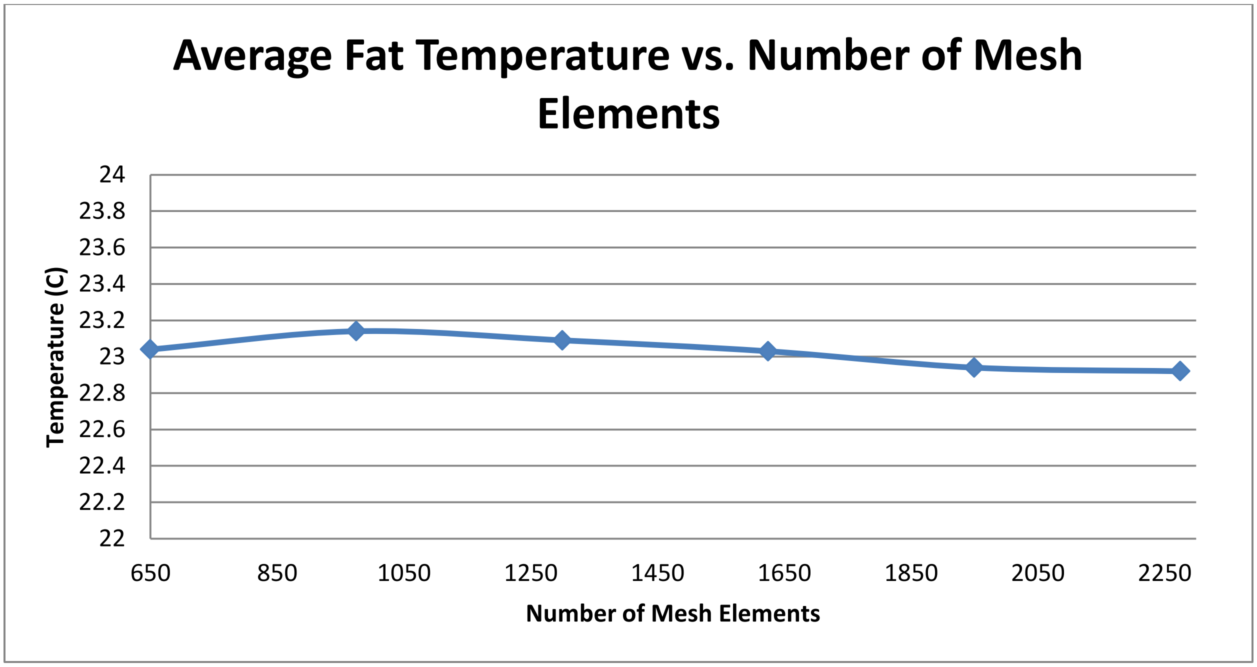

Figure1A: Mesh Convergence

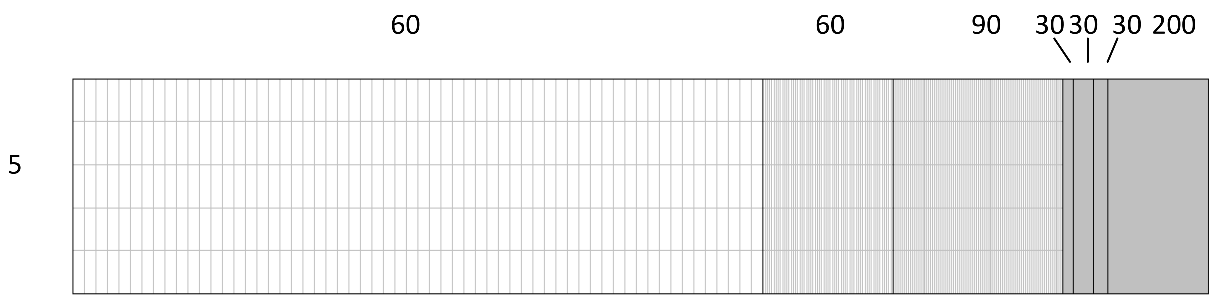

Figure2A: Final Mesh Layout for a person with a 21 BMI wearing a coat

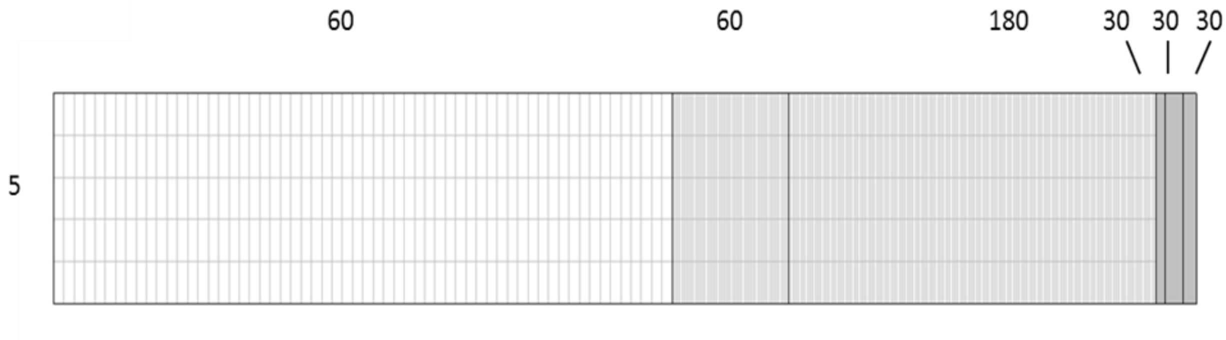

Figure 3A: Final Mesh Layout for a person with a 28 BMI wearing a T-shirt.

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5.4 Appendix D - References

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